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Study of Damage in Woven Composite Materials Subjected to Impact

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Abstract: This study focuses on modeling the low-velocity impact behaviour of textile-shaped composites. Textile preforms are modeled using Texgen software. Six types of fabrics are considered: Twill (2/2) [0]4, twill (2/2) sequence [0/30/-30/0], twill (2/2) sequence [0/45/-45/0], and plain weave [0]4, plain weave sequence [0/30/-30/0], plain weave sequence [0/45/-45/0]. For the study of fabric damage under impact, the commercial finite element software Ls-dyna is used in transient regime. The "automatic-surface to-surface" approach is employed to model the contact between the impactor and the laminate, while the contact between fibres and the matrix is modeled using the "contact automatic surface to surface tiebreak" technique. Results from the modeling are graphically represented over the impact time. With increasing impact velocity, the contact force, displacement at the impact point, and impact energy increase accordingly.

Keywords: keyword; woven composite; Ls-dyna; Texgen; impact.

1. Introduction

Currently, composite materials constitute a significant revolution in the industry due to their mechanical and thermal qualities, ensuring their suitability for operation under various conditions. Composites exhibit excellent behaviour in fatigue, corrosion, impact resistance, and chemical attacks. However, their use remains limited compared to traditional materials, primarily due to the lack of a comprehensive database on their mechanical properties and performance in service conditions.

Today, textile preform composites, whether two-dimensional or three-dimensional, are widely employed. These materials demonstrate good behaviour compared to unidirectional composites. Tiziana Segreto et al. [1] studied the influence of impact conditions on damage formation in high-performance composite materials, such as fabric-shaped laminates, using advanced non-destructive evaluation techniques like whole-volume ultrasonic scanning. This technique is based on the pulse-echo immersion method and allows quantitative analysis of the internal structure throughout the composite volume. Achache et al [2] presented a numerical method for evaluating the stress concentration factor (SCF) in three-dimensional laminated composites under mechanical loads. The proposed method uses the finite element formulation. In order, the results obtained by this study are compared with those reported in the literature. The aim of this analysis is to numerically evaluate the stress concentration factor under the influence of several parameters such as fibre orientation, mechanical characteristics of composites and the distance between notches of cross laminates. M. Chandrashekhar et al. [3] qualitatively estimated impact effects and developed a robust Fuzzy Logic System (FLS) for detecting delamination damage in composite plate structures. Their model is based on statistical information obtained from numerical studies and utilizes modal frequencies of the composite. Any attempt to manufacture laminates resistant to low-velocity impact damage must begin with an understanding of the sequence of

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rupture mechanisms. To this end, a series of quasi-static indentation tests were conducted on AS4D/TC350 carbon/epoxy samples by A. Wagih et al. [4].

Various models have been presented in the literature to predict the behaviour of composites subjected to low-velocity impact. These models describe damage evolution exponentially or linearly with deformation. Achache et al [5] numerically analysed in three dimensions by the finite element method of a mechanical load on the delamination of unidirectional and multidirectional composite laminates in order to determine the energy release rate G in Mode I and the equivalent Von Mises stress distribution along the damaged zone under the influence of several parameters such as the applied load and the size of the delamination. The results obtained in this study show that unidirectional composite laminates have better mechanical resistance on the loading line than multidirectional composite laminates. Low-velocity impact simulations for an E-glass/epoxy composite are performed using 'a material model based on continuum damage mechanics and compared with experiments by Singh et al [6]. The damage observed through the projected area of light on the laminate, the contact forces and displacement plots in function of time were studied and compared with the results of finite element analysis to demonstrate the effectiveness of the model. Digital image correlation (DIC) technique was used for the experiment to obtain displacement on the surface of the plate. Chaib et al [7] focused-on core-cracked samples of 6000 series M(T) 6061 T6 aluminium alloy and presented a comprehensive review of the effect of patch repairs composite on fatigue deterioration of aeronautical structures. Their results highlight the interdependence of geometric and mechanical properties between the composite patch, the adhesive and the damaged structure. Eun-Ho Kim et al. [8] proposed a composite damage model based on Continuum Damage Mechanics (CDM) for the progressive analysis of damage in composite structures. The progressive damage law considers the Weibull distribution of composite strength and was implemented in the ABAQUS/Explicit program using the VUMAT subroutine. Zahi et al [10] developed a program to calculate the natural frequencies and critical speeds of the system. This advanced finite element approach aims to analyse the vibration behaviour of rotors with tapered composite shafts, taking into account the 'impact of clearance angle on the stiffness of composite shaft laminate. The results obtained are compared with those available in the literature. This research provides valuable information on the vibration behaviour of rotors with tapered composite shaft and can be useful for the design and optimization of such structures in various industrial applications. Khalfi et al [11] used numerical optimization to determine the main impact factors affecting crack repair in pipeline structures using composite material patches. Zahi et al [12] presented an advanced finite element formulation to analyse the vibration behaviour of tapered composite shaft rotors, considering the impact of the clearance angle on the stiffness of the composite shaft laminate. Achache et al [13] studied numerically by the finite element method, the durability of structures damaged and repaired by hybrid composite patches under the effect of a mechanical load coupled with environmental conditions (water absorption and/or temperature). The results of this study allowed the authors to conclude that the [0°]8 sequence systematically offers the best performances, with the lowest J-integral values and superior crack resistance. Achache et al [14] analysed by the finite element method the evolution of the KI parameter stress intensity factor of two representative elementary volumes (REV) made up of the same epoxy matrix and different reinforcing fibres (Alfa and Glass) as a function of the displacement of the two fibres (a) and (b). The numerical study showed that the position of the fibres has a significant role on the composite material as well as the REV alfa/epoxy behaves better than the REV glass/epoxy due to the good mechanical characteristics of REV alfa/epoxy.

2. Mathematical Model / Experimental Method

2.1. Impact Theory

The dynamic equilibrium of the impactor is achieved through Newton's law [6].

$$m_i \ddot{w} + F_c = 0 \tag{1}$$

With: m_i - mass of the impactor; $\ddot{w}$ - acceleration of the impactor; F_c - contact force.

The Hertz contact law:

For loading $F_c = k\alpha_i^{3/2}$ (2)

With: k - coefficient; α_i - indentation depth.

For unloading $$F_c = F_m\left[\frac{\alpha_i-\alpha_0}{\alpha_m-\alpha_0}\right]\left[\frac{\alpha_i-\alpha_0}{\alpha_m-\alpha_0}\right]^{\frac{5}{2}}$$

With: α_m - maximum indentation; α_0 - initial indentation; F_m - maximum contact force.

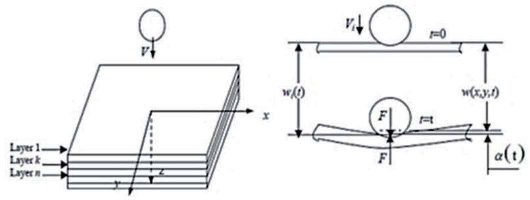

Figure 1: Basic model of impact damage

2.2. Woven Composite Studied

The textile-shaped preforms are modeled using Texgen software. Six types of fabrics are considered: Twill (2/2) [0]4, twill (2/2) sequence [0/30/-30/0], twill (2/2) sequence [0/45/-45/0], and plain weave [0]4, plain weave sequence [0/30/-30/0], plain weave sequence [0/45/-45/0], as shown in Figure (2). The geometry of fibres and matrix is depicted in Figures (2, 3), and the material properties of the composite used are provided in Table (1). The laminate samples consist of four layers with dimensions of 10x10x0.88 mm^3 and a ply thickness of approximately 0.22 mm.

An impactor with a hemispherical diameter of 2 mm was used to impact the composite at a velocity of 15 m/s. The analysis was performed using model 001-ELASTIC for the matrix, model 002-ORTHOTROPIC_ELASTIC for the fibres, and model MAT_020 for the impactor, as detailed in Table (1). For contact, the "automatic_surface_to_surface" approach was employed for fibres and the "automatic_surface_to_surface_tiebreak" approach for the fiber-matrix interface.

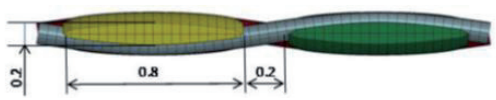

Figure 2: Fibre geometry

Table 1: Mechanical properties of fibres, matrix and impactor [6]

Constituents	Fibre	Matrix	Impactor
E11 (GPa)	186.8		
E22 (GPa)	3.5	2	207
E33 (GPa)	3.5		
v12	0.0016		
v13	0.0016	0.3	0.3
v23	0.4		
G12 (GPa)	14.37		
G13 (GPa)	14.37		
G23 (GPa)	14.37		
ρ (kg/mm^3)	1.628e-6	1.144e-6	7.85e-6

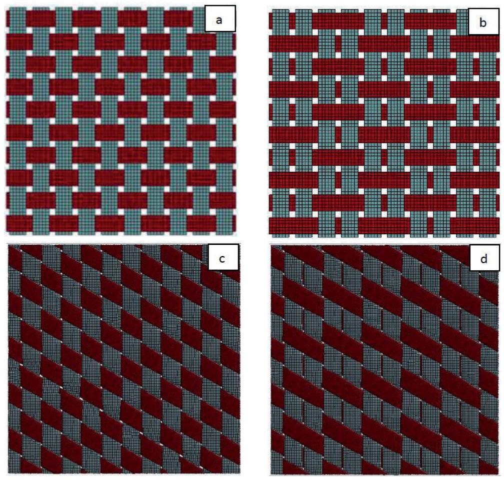

Figure 3: Fibre geometry

3. Results and Discussion

3.1. Force and Displacement

Figure 4a and 4b shows the displacement-time variations during impact. The [0/0]4 orientation consistently shows the highest displacement, indicating greater flexibility but lower resistance to impact forces. Conversely, [0/45/-45/0] shows the lowest displacement, indicating higher stiffness and resistance to bending. Both weaves show similar trends in displacement, with plain weave exhibiting slightly lower peak displacements in some cases, suggesting it may offer marginally better resistance to deformation under impact. The displacement data reveals that altering the fibre orientation within the weave significantly affects the mechanical response to impact. Orientations with angled fibres ([0/30/-30/0] and [0/45/-45/0]) exhibit better resistance to displacement, which is critical for applications requiring high structural integrity under impact conditions.

Figure 5a and 5b presents contact force data as a function of impact time and provides insight into how different weave types and fibre orientations

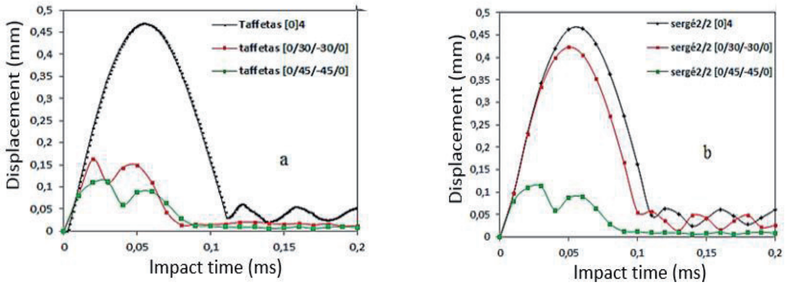

Figure 4: Displacement vs. Impact Time: (a) Plain weave; (b) twill 2/2

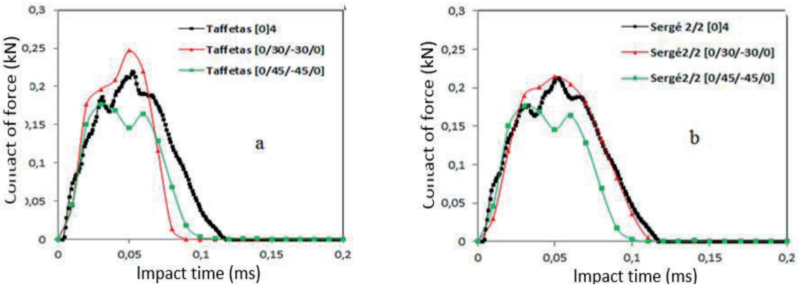

Figure 5: Contact Force vs. Impact Time: (a) Plain weave; (b) twill 2/2

affect the impact resistance of composite materials. Among the fibre orientations, [0/30/-30/0] consistently exhibits the highest impact strength, with values reaching 0.245 kN, making it the preferred configuration for applications requiring high shock absorption. The 2/2 twill also has a high contact force, reaching 0.221 kN. These results indicate that inclined fabrics experience higher forces upon impact, likely due to their specific weave orientations and structural responses. They are crucial for the design of composite materials for applications where resistance to shock is essential, such as in the aerospace, automotive and protective equipment sectors.

For a more comprehensive scientific analysis, additional details such as stress-strain relationships, energy absorption capabilities, and specific mechanical properties over time would provide deeper insights into the impact behaviour of these woven composites.

3.2. Delaminated Area

In the context of delamination, the extent of damage varies significantly among different fabric types. The inclined plain weave (taffetas) and twill 2/2 [0/45/-45/0] configurations exhibit comparatively smaller delaminated surfaces.

Specifically, for twill 2/2 [0]4, a substantial delaminated area of approximately 9.224 mm^2 is observed in the third interface. This indicates significant separation and damage propagation within the laminate structure under impact conditions. In comparison, plain weave [0]4 shows a delaminated area of 7.959 mm^2 in the same interface.

These findings suggest that the delamination behaviour is influenced by the weave pattern and orientation of the fibres, impacting the laminate's resistance to damage propagation. Further detailed analysis would involve understanding the stress concentrations, failure modes, and interfacial bonding characteristics contributing to delamination in these woven composites.

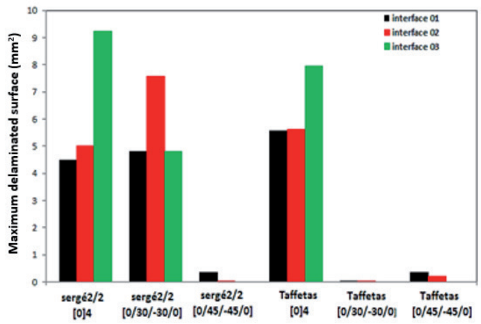

Figure 6: Maximum Delaminated Area

4. Conclusions

Textile preform composites, whether two-dimensional or three-dimensional, are extensively utilized due to their superior mechanical properties compared to unidirectional composites. This study considered several types of fabrics, including unidirectional, plain weave (taffetas), twill weave (sergé), and twill 2/2, with variations in stacking sequences at inclinations of 30° and 45°. The research aimed to elucidate the distinct failure mechanisms induced by low-velocity impact.

It is observed that inclined fabrics such as plain weave [0/30/-30/0] and twill 2/2 [0/30/-30/0] exhibit higher stiffness compared to their non-inclined counterparts. This indicates a potentially lower susceptibility to deformation under impact loading. Overall, woven composites demonstrate significant resistance to rupture and delamination, highlighting their robust mechanical performance.

The findings emphasize the critical role of fabric orientation and stacking sequence in influencing the structural integrity and damage tolerance of textile-based composites. Future research could focus on further optimizing these parameters to enhance the overall durability and performance characteristics of such materials in practical applications. Advanced analytical techniques and detailed numerical simulations could provide deeper insights into the underlying failure mechanisms and enable more precise predictions of composite behaviour under impact conditions.

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